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MATLAB PROGRAM BASED TEMPERATURE ESTIMATION OF MOTORS BY DIFFERENT TNM MODELS

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ABSTRACT

This paper presents MATLAB Program Based Temperature Estimation of Motors by Different thermal network method (TNM) Models for analyzing Squirrel cage induction motors (SCIM). A general MATLAB program has been developed for the solution of some important TNM models that are available in literature. Comparison of accuracies has been discussed for estimation of hot spot temperatures. Simplifications and validity of simplifications in the investigation of thermal resistances from the point of accuracies expected; case wise also have been discussed. Results obtained for the 30 KW motor for the selected TNM models have been compared. Listing of the MATLAB program is presented as annexure.

KEYWORDS: MATLAB Program, Seven TNM Models, Analyzing Squirrel Cage Induction Motors SCIM motors

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Original Article

I. INTRODUCTION

MATLAB program solutions for seven TNM models that are available in literature have been discussed in this report. The TNM models are 2 node, 4 node, 5 node, 6 node, 8 node, 11 node and 10 node. All these models have been developed by different authors working for different Institutions or Organizations. The motives of developing all these TNM models are different and have been mentioned in the corresponding reports. A comparison of methods of solutions by these models has been made in this report. A general MATLAB program is developed for temperature rise calculation at nodes of these TNM models based on the procedures mentioned in these reports. Details for estimation of thermal resistances for two models, viz., the 5 node and the 10 node TNM models are available.

Owing to heterogeneity of components, SCIM motors constitute a complex field of thermal study. However, the symmetries existing in motors or symmetries obtained because of simplifications allow the motor to be divided into finite number of nodes. Geometrical dimensions, motor assembly information, material thermal properties, idea of losses and their distribution together with the required accuracies in thermal distribution evaluation for each motor decide usage of a specific thermal network model once the thermal resistances are calculated. Governing equations for solving equations involving conductivity, loss and temperature rise matrices; are formed. Comparison of MATLAB program results with that of results mentioned in the referred report for the specific TNM model are also made. Two different approaches are followed for evaluation of thermal resistances.

The first one is a simpler approach for evaluation of thermal resistances as explained in report 2 and is used for 2 Node and 5 Node TNM models. Same notations as available in the specified report are used in the MATLAB program corresponding to the TNM 5 node model.

If the temperatures at certain locations by a TNM of lesser number of nodes are found to be critical or margins of safety are quiet less, it is advisable to use a TNM of higher number of nodes since the lower numbers are highly conservative. As nodes in the TNM models increase, some assumptions for simplifications in the models are avoided and a TNM model to make it close to the actual situation of the motor as presented by Mellor is followed.

Suitable convective heat transfer coefficients are selected and the conductivity matrix is arrived at. The vector of temperature rise matrix is arrived at

$\Delta\theta = G^{-1} p.$

With the above equation, it is possible to determine average temperatures of various parts of stator and rotor, establishing thermal fluxes transmitted along thermal network paths.

For models of 6 nodes TNM and 8 nodes TNM, formation of governing equations and corresponding MATLAB programs only are discussed in this report. This is done because it is felt the TNM proposed in report 2 of 5 nodes and 13 resistances discussed in Part E is more useful as compared to TNM of 6 nodes and10 resistances of Part C for the selected motor. It is also felt that the TNM proposed in reports 1, 10 of 10 nodes and 37 resistances which has been discussed in section G is more useful compared to TNM of 8 nodes and eleven resistances of Part D. TNM of 11 nodes and 14 resistances of report 9 is applicable when thermal conditions at fan end and no fan end differ very much. Table 2 gives the flow of heat among various components of motor which together with figures. 1 and 2 describe the TNM layouts. Grouping of heat flows corresponding to a particular node and the color code corresponding to the particular TNM model takes care of the layout representation of the specific TNM model.

Reference reports' details of different TNM models are indicated in table 1. Consistent notations for thermal resistances have been established. Define thermal design improvement targets and all the constraints of motor making and thermal limits together dictate the selection of a particular TNM model. The SCIM motor data available for a particular TNM is recorded. For all the models conductivity matrices are constructed based on the governing equations. A negative sign indicates heat leaving the node whereas a positive sign indicates heat reaching the node or heat generation at the node.

Table 1: Report Layout

Sl. No.	Part	Report	TNM Model	Motor on Which it is Applied
1	A	5	2	--
2	B	6	4	3.8 KW
3	C	7	6	--
4	D	2	5	--
5	E	3	8	--
6	F	9	11	7.5 KW
7	G	1,4	10	30 KW

A Heat Flow among Various Components

Table 2: Flow of Heat in the Motor

No.	Location of Heat Flow	Nature of Heat Transfer
1	Frame to Ambient	Convection/Radiation
2	Stator core to Frame	Contact Resistance and conduction
3	Stator core to stator teeth	Conduction
4	Stator teeth to Stator winding	Bi-directional heat flow
5	Stator winding to stator end winding	Conduction Bi-directional
6	Stator end winding to end cap air	Convection
7	Stator teeth to Air gap	Natural convection/conduction
8	Air gap to Rotor teeth	
Forced convection for high speeds and higher length of air gap and for low speeds and smaller air gap it may be treated as conduction by air		
9	Rotor teeth to Rotor core	Conduction
10	Rotor teeth to Rotor bars	Conduction
11	Rotor bars to Rotor end ring	Conduction
12	Rotor core to Shaft	Conduction
13	Shaft to End cap air	Convection/Radiation
14	End cap air to frame	Convection/Radiation
15	Rotor end rings to end cap air	Convection
16	Stator core to End cap air	Convection/Radiation

II PART A - TNM OF TWO NODES

Refer the heat exchange layout corresponding to Dark red blocks of figure 1[8]. The simplest of all the lumped thermal models is obtained by dividing the given induction motor into three basic thermal blocks (units) viz., stator rotor gap (air gap), stator including the frame and rotor.

A, Salient Features of the Model

- Heat dissipation or flow between stator as one single unit and environment as other. This is two-fold in the simplest way assumed. One is from stator winding to stator end winding and then to end cap air of the frame of stator and then to the environment.
- Heat flow from rotor as a single unit to environment. Heat flow from rotor to environment (For Rotor teeth heat flow there are two parallel paths a) to rotor core, shaft, end cap air to end cap and b) to rotor bars, rotor end ring to end cap and then from both parallel paths to ambient.
- Resistance to Heat flow between rotor and stator in the form of air gap.

This method could be used in average temperature rises of stator and rotor and adopted in the optimization schemes for minimum temperature rise of SCIM motors.

$$R_s = \frac{1}{2\pi\, k_{S,e}\, L} \ln \frac{r_{o,s}}{r_{i,s}} \qquad R_r = \frac{1}{2\pi\, k_{R,e,}\, L} \ln \frac{r_{o,r}}{r_{i,r}}$$

Where r_o and r_i correspond to outer and inner radii and r for rotor and s for stator. Also $K_{S,e}$ is the equivalent for the combined scheme of resistances R_s for stator and $K_{R,e}$ is the equivalent for the combined scheme of resistances R_r for Rotor

B. Governing Equations

$$\left(\frac{1}{R_s}+\frac{1}{R_{sr}}\right)\Delta\theta_{s,} - \left(\frac{1}{R_r}+\frac{1}{R_{sr}}\right)\Delta\theta_{r,} = P_s \text{ or } \quad G_{11}\,\Delta\theta_{s,} - G_{12}\,\Delta\theta_{r} = P_s$$

$$\frac{1}{R_{sr}}\,\Delta\theta_{s,,}+,\left(\frac{1}{R_r}+\frac{1}{R_{sr}}\right)\Delta\theta_{r,} = P_r \qquad \text{or } -G_{12}\,\Delta\theta_{s,} + G_{22}\,\Delta\theta_{r,} = P_r$$

Heat flow paths are as indicated in the figure 1 and nodes are marked by dark red colour.

C. Conductivity Matrix (G) Estimation

$$G_{11} = \frac{1}{R_s}+\frac{1}{R_{sr}} \; G_{22} = \frac{1}{R_r}+\frac{1}{R_{sr}} \; G_{12} = \frac{1}{R_{sr}} \; G_{21} = \frac{1}{R_{sr}}$$

The governing matrix for temperature rise of,steady state is

$$\begin{bmatrix} G_{11} & -G_{12} \\ -G_{21} & G_{22} \end{bmatrix}\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \end{bmatrix} = \begin{vmatrix} P_1 \\ P_2 \end{vmatrix}$$

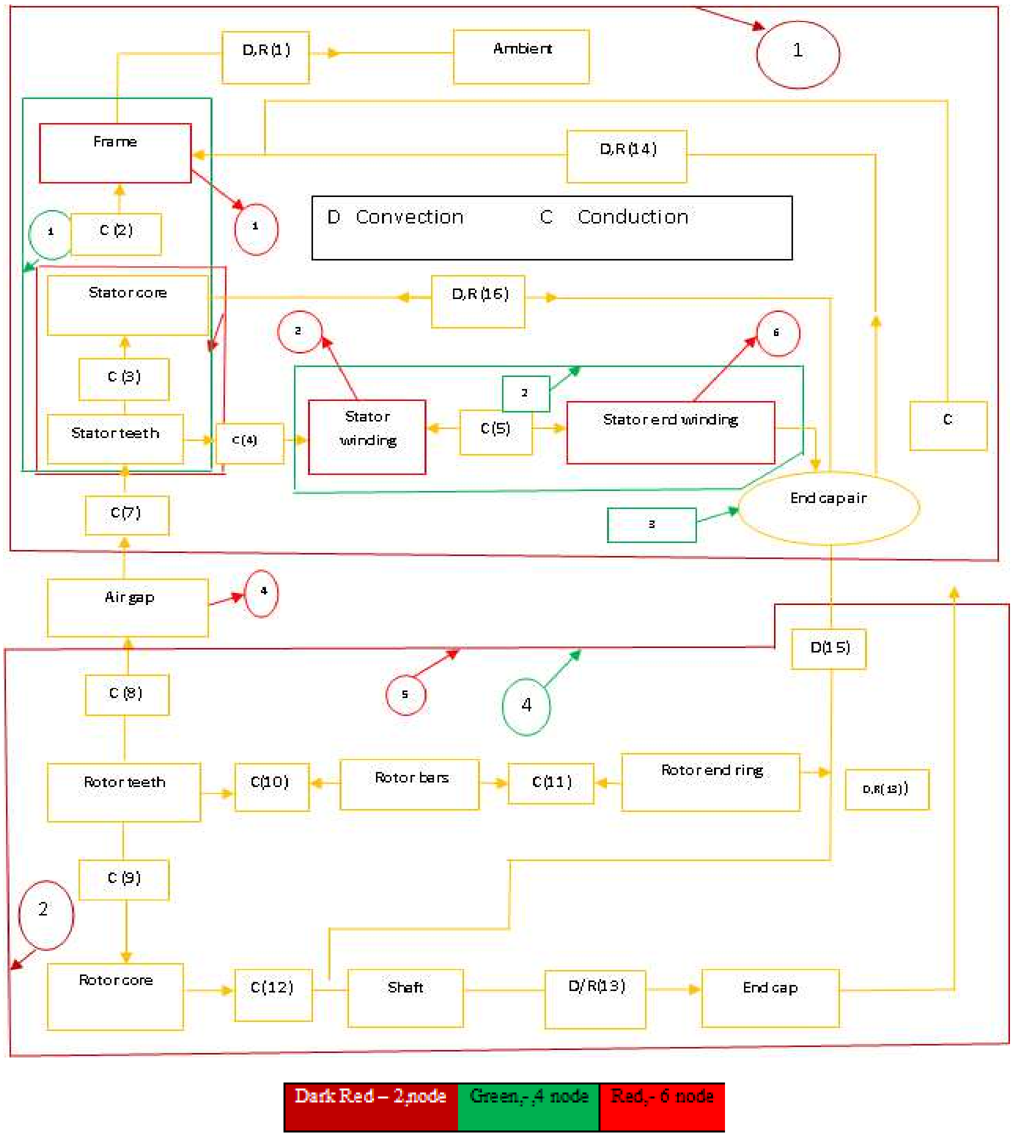
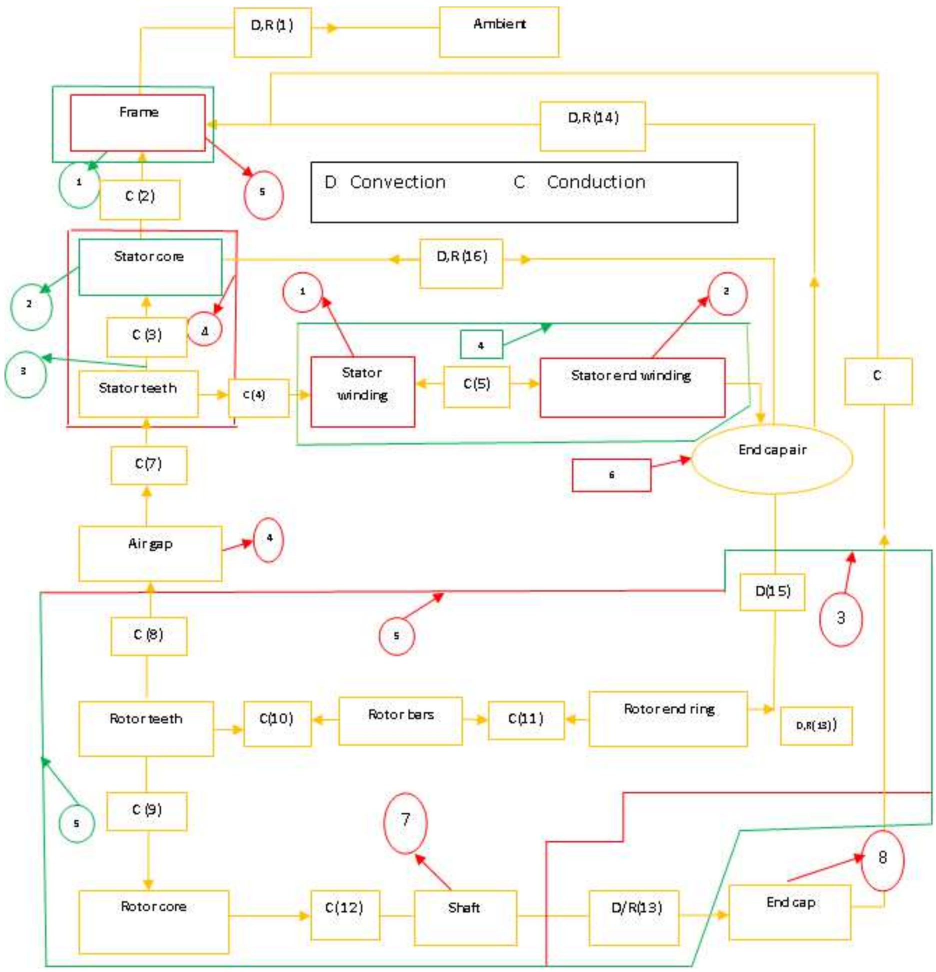


Figure 1: Thermal Network Layout



Green,-,5 node | Red,- 8 node

Figure 2: Thermal Network Layout

Rotor is treated as one single identity for resistance calculations and for heat distributions. This simplification is possible a) When the lamination steel conductivity and rotor bars and end ring material conductivity values are close and b) The end ring and copper bar heat loss volumetric densities do not differ very much. Rotor core losses, friction and wind age and additional losses of rotor are quiet small compared to stator core losses, stator copper losses and rotor copper losses. Frame material is a good conductor of heat (cast Al frame or better conductor of heat) and thickness of frame needs to be small for Four Node TNM model. Stator core losses are high in 5 Node TNM and contact resistance is significant. Frame is thicker and is made of inferior conductor of heat.

Table 3: Temperature Distributions for Two Node TNM Model

Details of Motor					
Tooth Area Mm^2	**Alpha**	**Tot_ Area**	**Tsy Shown In Figure 3**	**Velocity**	**Re**
230.83	0.60	0.973	0.0339	16.75	5.08e05
	Pr	Nu	h_{ea}	Air gap	
	0.72	1128.	53.57	0.8	
Conductivity Values of Motor Materials					
Air =0.03		Shaft= 65.55		Iron =65.55	
Interfere	tec	teq	lsb	Slot fill factor	

nce gap						
	Nomenclature is as given in figure 3					
1.60e-5	4.74e-2	1.38e-2	8.38e-3	0.5		
slots	Length	Radius	Core outer radius	Frame inner radius		
48	0.207	0.1067	0.135	0.169		
Tooth outer radius	Rotor core radius	Shaft radius	Frame thickness			
0.1075	0.089	0.055	0.047			
	All dimensions are in m					
Length of frame	Length of shaft	Length of end caps	Shaft extension	Slot area $x10^6$	Copper area $x10^6$	
m				m^2		
0.64	0.75		0.11	231	191	
Resistances			Heat input (W)	Temperature rise		
R_s K/W	R_{sr} K/W	R_r K/W	Stator	Rotor		
.0106	0.188	0.130	1300.0	500.0	10.85	40.68
Conductivity matrix						

	1	2
1	146.16	-5.31
2	-5.31	17.47

In the following table a comparison of 4 node, 5 node and 6 node TNM models has been brought out and users are advised to go through these before a choice of the TNM model is made.

Table 4: Comparison of 4 Node, 5 Node and 6 Node TNM Models

6 Nodes
Stator winding, end winding stator core, Air gap, Rotor and frame are the nodes.
Building of conductivity matrix and only governing equations relating temperature rise, heat loss and conductivity matrix is presented. Stator end winding length is larger and end windings heat gets dissipated through end spaces. Red color boundary lines are used in figure 1.
5 Nodes
Frame, yoke middle, stator core are three nodes. Both Stator winding and end winding are grouped as one). Shaft is part of rotor and copper losses are applied on rotor. Air gap resistances are added between rotor and stator yoke nodes. Method has been applied for solving temperature distributions in case of 30 KW motors. Green color boundary lines are used in figure 2.
4 Nodes
Motor frame and stator core are combined as one node. Stator winding and end windings are treated as one. Rotor bars and rotor end rings are treated as one entity as heat loss density values are almost same in rotor bars and end rings and rotor cores. End cap air is another node in this model. Conductor insulation thickness is less and thermal conductivity of conductor insulations are relatively higher. Green color boundary lines are used in figure 1.
Contact resistance is part of stator node.

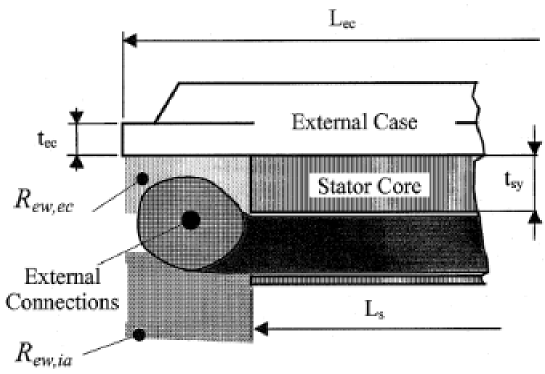


Figure 3: Dimensional Details of Motor

III. PART B TNM OF FOUR NODES AND SIX THERMAL RESISTANCES

Simplified method of estimation of resistances which has been explained in section IV could be used for evaluation of various resistances. The second simplest way of estimation of rotor temperature presented by Okonkwo [6] is by 4 node TNM model.

Motor frame and stator laminations node consists of Frame, Stator core, teeth and frame and corresponding resistances mentioned in Green color blocks of figure 1.

A. Resistances to Heat Flows of Table 1 -Figure 1

R_{1a} is the resistance to the heat flow from Stator stack without windings to the ambient. Resistances 1 to 3 are combined as R_{13} which is the resistance to the heat flow from stator stack without windings to rotor winding. Air gap resistance is part of the resistance. And similarly resistances 6 and 7 are combined as R_{12}. Stator winding node consists of embedded windings in the slots and end windings. R_{24} is the resistance to heat flow from Stator winding to stator end cap air. R_{4b} or R_{4a} is the resistance to heat flow from end cap air to ambient.

Rotor node and corresponding resistance consist of rotor bars embedded end rings, shaft with boundary lines for rotor. Resistances 9 to 16 are combined as single resistance and treated as R_{13}, R_{34} is the resistance to the heat flow from rotor windings to end cap air of the stator frame. R_{34} and R_{4a} correspond to resistance to heat flow from rotor end ring to end cap and from end cap to ambient.

This TNM is based on the following assumptions:

Total heat generated in rotor bars and end rings (also frictional losses and part of additional loss) is dissipated to the environment end cap and then to the ambient.

- Total heat generated in stator laminations and windings including the end windings is added on to the Motor frame and stator lamination node and dissipated to the ambient by convection.
- Rotor copper losses (bars and end rings together is added at the rotor winding node)
- Additional loss or stray loss is added to stator (30 %),,to stator laminations (40 %) and 30% to rotor core
- Mechanical losses are added to rotor only.

The effect of simplifications is that the heat transfer from the rotor winding through the air-gap goes directly to

the stator winding with negligible impact on the stator teeth. Any heat transfer due to radiation from the internal surfaces is neglected. Thermal network model for the motor is realized by connecting the networks for the rotor, stator and frame together.

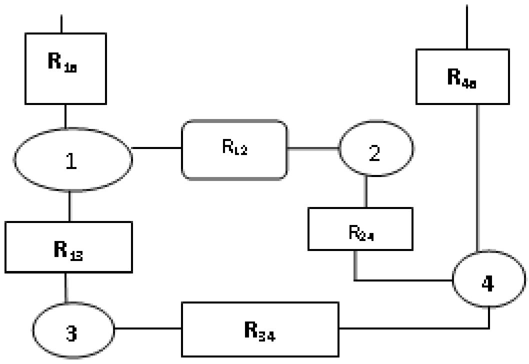


Figure 4: TNM Model of 4 Nodes

A. Governing Equations

$$P_1 = \frac{1}{R_{12}}(\theta_1-\theta_2) + \frac{1}{R_{1a}}(\theta_1-\theta_a) + \frac{1}{R_{13}}(\theta_1-\theta_2) = g_{11}\,\Delta\theta_1 - g_{12}\,\Delta\theta_2 - g_{13}\,\Delta\theta_3 - g_{14}\,\Delta\theta_4$$

$$P_2 = \frac{1}{R_{12}}(\theta_2-\theta_1) + \frac{1}{R_{24}}(\theta_2-\theta_4) = -g_{12}\,\Delta\theta_1 + g_{22}\,\Delta\theta_2, - g_{23}\,\Delta\theta_3 - g_{24}\,\Delta\theta_4$$

$$P_3 = \frac{1}{R_{23}}(\theta_3-\theta_1) + \frac{1}{R_{34}}(\theta_3-\theta_4) = -g_{13}\,\Delta\theta_1 - g_{23}\,\Delta\theta_2 + g_{33}\,\Delta\theta_3 - g_{34}\,\Delta\theta_4$$

$$P_4 = \frac{1}{R_{34}}(\theta_4-\theta_3) + \frac{1}{R_{4b}}(\theta_4-\theta_b) - \frac{1}{R_{24}}(\theta_4-\theta_2) = -g_{41}\,\Delta\theta_1 - g_{24}\,\Delta\theta_2 - g_{34}\,\Delta\theta_3 + g_{44,}\Delta\theta_4$$

B. Conductivity Values

$G_{1a}=1/R_{1a}$; $G_{12}=1/R_{12}$; $G_{13}=1/R_{13}$; $G_{14}=0.0$; $G_{24}=1/r_{24}$;$G_{34}=1/r_{34}$; $G_{4b}=1/r_{4b}$; $G_{23}=0.0$;

$G_{11} = G_{13} + G_{12} + 1/r_{1a}$;

$G_{22} = G_{12} + G_{24}$;

$G_{33} = G_{13} + G_{34}$;

$G_{44} = G_{24} + G_{34} + 1/r_{4b}$;

Table 5: Temperature Distributions for a Four Node TNM

Resistance Values of 4.8 KW, SCIM Motor						
Resistances	r1a	r12	r24	r34	r13	r4b
Values	0.042	.01075	0.16	0.09	0.135	0.015
Conductivity Matrix						
	1	2	3	4	Ambient	
1	124.47	-93.02	-7.41	-0.00	24.04	
2	-93.02	99.27	-0.00	-6.25		
3	-7.41	-0.00	17.96	-10.55		
4	-0.00	-6.25	-10.55	83.47	66.67	
Heat Flow Values Around the Nodes						

Heat Generation	Heat Flows Around Node			Temperature Details at the Node	
Node 1- Motor Frame and Stator Laminations					
223.	q1a	q21	q31	43.13	23.13
	-556	327.72	5.30		
Node 2 - Stator winding					
463.	q24	q21		46.65	26.65
	-135.3	-327.7			
Node 3 - Rotor winding					
204.0	q31	q34		43.87	23.87
	-5.3	-198.7			
Node 4- End cap					
0.0	q24	q34	q4b	25.01	5.01
	135.3	198.70	-334.0		
Iron losses	Stator copper losses	Rotor copper losses	Frictiona l losses	Additional losses	
181.0	463.0	140.0	22.0	84.0	

IV. PART C TNM OF SIX NODES AND EIGHT RESISTANCES

This is a six node eight resistance TNM model and is based on principles explained in report 7. Refer red color blocks of figure 1.

Only formation of governing equations and corresponding MATLAB program of this TNM is discussed in this report as it is felt this TNM is less useful compared to the TNM proposed in report 2 for the motors analyzed which is discussed in section D. P_1 - Copper Losses in end sections of the stator (end winding). P_2 - Losses in copper in slot part of the stator P_3 - Losses in iron yoke and teeth of the stator P_5Losses in copper bars and end rings of Rotor. There is no heat at node 4 or P_4 =0.0 Part of mechanical friction losses is dissipated over end caps. A part of the friction losses is dissipated into side air spaces. Stray losses are distributed into nodes as they occur.

A. Governing Equations

$$P_1 = \frac{1}{R_{12}}(\theta_1 - \theta_2) + \frac{1}{R_F}(\theta_1 - \theta_F) + \frac{1}{R_{15}}(\theta_1 - \theta_5) + \frac{1}{R_{14}}(\theta_1 - \theta_4)$$

$$P_2 = \frac{1}{R_{12}}(\theta_2 - \theta_1) + \frac{1}{R_{26}}(\theta_2 - \theta_6)$$

$$P_3 = \frac{1}{R_{34}}(\theta_3 - \theta_4) + \frac{1}{R_{35}}(\theta_3 - \theta_5) + \frac{1}{R_{32}}(\theta_3 - \theta_2)$$

$$P_4 = \frac{1}{R_{14}}(\theta_4 - \theta_1) + \frac{1}{R_{45}}(\theta_4 - \theta_5) + \frac{1}{R_{46}}(\theta_4 - \theta_6)$$

$$P_5 = \frac{1}{R_{45}}(\theta_5 - \theta_4) + \frac{1}{R_{15}}(\theta_5 - \theta_1)$$

$$P_6 = \frac{1}{R_{46}}(\theta_6 - \theta_4) + \frac{1}{R_{62}}(\theta_6 - \theta_2)$$

B. The Conductivity Values

$G_{56}=1/R_{56}$; $G_{12}=1/R_{12}$; $G_{15}=1/R_{15}$;$G_{14}=/R_{14}$

$G_{46}=1/r_{46}$; $G_{15}=1/r_{15}$; $G_{45}=1/r_{45}$; $G_{34}=1/R_{34}$; $G_{32}=1/R_{32}$

$G_{11} = G_{15} + G_{12} + G14 + 1/r_F$; $G_{22} = G_{12} + G_{26}$;

$G_{33} = G_{34} + G_{35} + G_{32}$; $G_{44} = G_{14} + G_{45} + G_{46}$;

$G_{55} = G_{45} + G_{51}$; $G_{66} = G_{46} + G_{62}$;

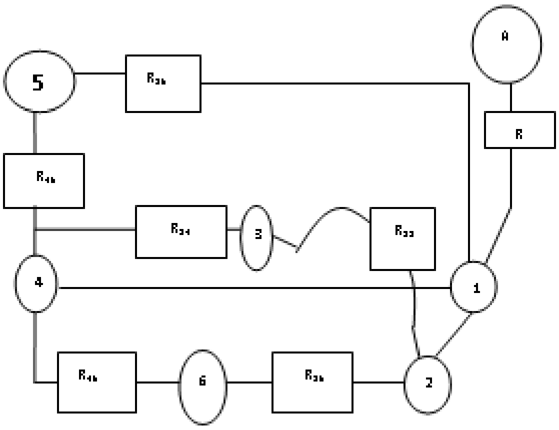


Figure 5: TNM of Six Nodes

V PART D TNM OF EIGHT NODES [3]

Only formation of governing equations and corresponding MATLAB program of this TNM is discussed in this report. This is because for the motors for which efficiency improvement along with thermal design improvements are considered, it is felt that this TNM is less useful compared to the TNM proposed in report 2 which is discussed in section E. Refer red color blocks of figure 2.

A. Governing Equations

Table 6 Thermal Resistance Values and Their Description

Sl No, R*	R*- Resistance Description	[K/W] Value
13,R_{shf}	Axial conduction thermal resistance of the shaft	0.0887
12,R_{sig}	Conduction resistance of the interface gap between the stator core and the external case	0.0024
11,$R_{r,ag}$	Convection thermal resistance between rotor and air gap air	0.1897
10,$R_{s,ag}$	Convection thermal resistance between stator teeth and air gap air	0.1883
9,$R_{ew,ia}$	Convection thermal resistance between stator winding external connections and inner air	0.2692
8,$R_{ew,ec}$	Convection thermal resistance between stator winding external connections and external case	0.0027
7,$R_{cu,ir}$	Convection thermal resistance between stator copper and stator slot	3.0374
6, R_{st}	Radial conduction thermal resistance of the stator teeth	0.0054
5,R_{sy2}	Radial conduction thermal resistance of the stator yoke upper teeth	0.0012

4,R_{sy1}	Radial conduction thermal resistance of the stator yoke lower teeth	0.0014
3,$R_{ia,ec}$	Convection thermal resistance between internal air and end caps	0.0728
2,R_o	Natural Convection thermal resistance between external case and ambient	0.1962
1,R_{eca}	Forced convection thermal resistance between external case and ambient	0.0340
0,R_{airgap}	If heat transfer in air gap is by conduction and not by convection	

$$P_1 = \frac{1}{R_{14}}(\theta_1 - \theta_4) + \frac{1}{R_{12}}(\theta_1 - \theta_2) + \frac{1}{R_{13}}(\theta_1 - \theta_3)$$

$$P_2 = \frac{1}{R_{12}}(\theta_2 - \theta_1) + \frac{1}{R_{26}}(\theta_2 - \theta_6)$$

$$P_3 = \frac{1}{R_{37}}(\theta_3 - \theta_7) + \frac{1}{R_{13}}(\theta_1 - \theta_3)$$

$$P_4 = \frac{1}{R_{14}}(\theta_4 - \theta_1) + \frac{1}{R_{45}}(\theta_4 - \theta_5)$$

$$P_5 = \frac{1}{R_{45}}(\theta_5 - \theta_4) + \frac{1}{R_{5a}}(\theta_5 - \theta_a)$$

$$P_6 = \frac{1}{R_{68}}(\theta_6 - \theta_8) + \frac{1}{R_{62}}(\theta_6 - \theta_2)$$

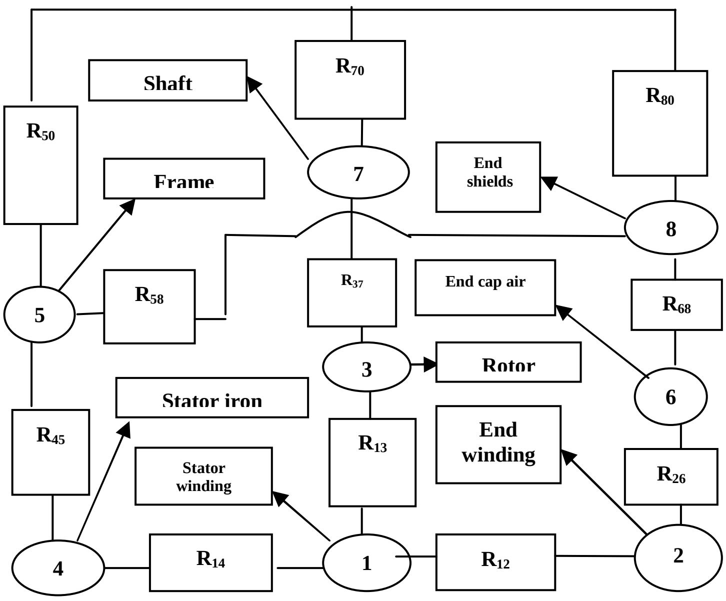


Figure 6: TNM of Eight Nodes

$$P_7 = \frac{1}{R_{7a}}(\theta_7 - \theta_a) + \frac{1}{R_{73}}(\theta_7 - \theta_3)$$

$$P_8 = \frac{1}{R_{8a}}(\theta_8 - \theta_a) + \frac{1}{R_{86}}(\theta_8 - \theta_6)$$

B. The Conductivity Values

$G_{37}=1/R_{37}$; $G_{13}=1/R_{13}$;$G_{12}=1/R_{12}$;$G_{14}=/R_{14}$

$G_{45}=1/R_{45}$; $G_{26}=1/R_{26}$;$G_{58}=1/R_{58}$;$G_{37}=1/R_{37}$;$G_{5a}=1/R_{5a}$

$G_{56}=1/R_{56}$; $G_{12}=1/R_{12}$;$G_{15}=1/R_{15}$;$G_{14}=/R_{14}$

$G_{8a}=1/R_{8a}$; $G_{7b}=1/R_{7b}$; $G_{11} = G_{13} + G_{12} +G_{14}$;

$G_{22} = G_{12} +G_{26}$; $G_{33} = G_{37}+ G_{31}$;

$G_{44} = G_{14}+ G_{45}$; $G_{55} = G_{45}+ G_{59}$,;

$G_{66} = G_{68}+ G_{26}$; $G_{77} = G_{45}+ G_{73}$,; $G_{88} = G_{7a}+ G_{86}$;

VI. PART E TNM OF FIVE NODES

This is a TNM of five nodes and twelve thermal resistances [2]. Validity of the approximations or simplifications has to be weighed before this TNM is used. Based on the simplified principles explained in report 2 the values of resistances have been calculated for 30 KW motor and detailed in table 6, 7 and 8. Temperature rises have been calculated. The evaluations for thermal resistances are presented as mathematical expressions in the MATLAB program which is given as an annexure. Same designation has been used for the variables mentioned in the equations of the report concerned and MATLAB variables. Refer green color blocks of figure 2 for the layout of TNM model.

Grouping of the resistances has been done as shown in the fig. 1 corresponding to resistances as described in the fig. 6.

Table 7: Temperature Distribution for the 5 Node TNM Model

1	2	3	4	5	Heat	Temp.
Node 1 -Frame						
1216.4	0.00	-275.0	-881.6	-7.68	0.0	38.81
Node 2 -Stator						
0.00	147.49	-141.7	-0.54	-5.29	0.0	43.76
Node 3 – Stator Yoke						
-275.0	-141.7	416.69	0.00	0.00	630.	42.01
Node 4 – Stator winding						
- 881.6	-0. 54	0.00	882.12	0.00	740.	39.66
Node 5 – Rotor winding						
-7.68	-5.29	0.00	0.0	12.98	653.00	91.16

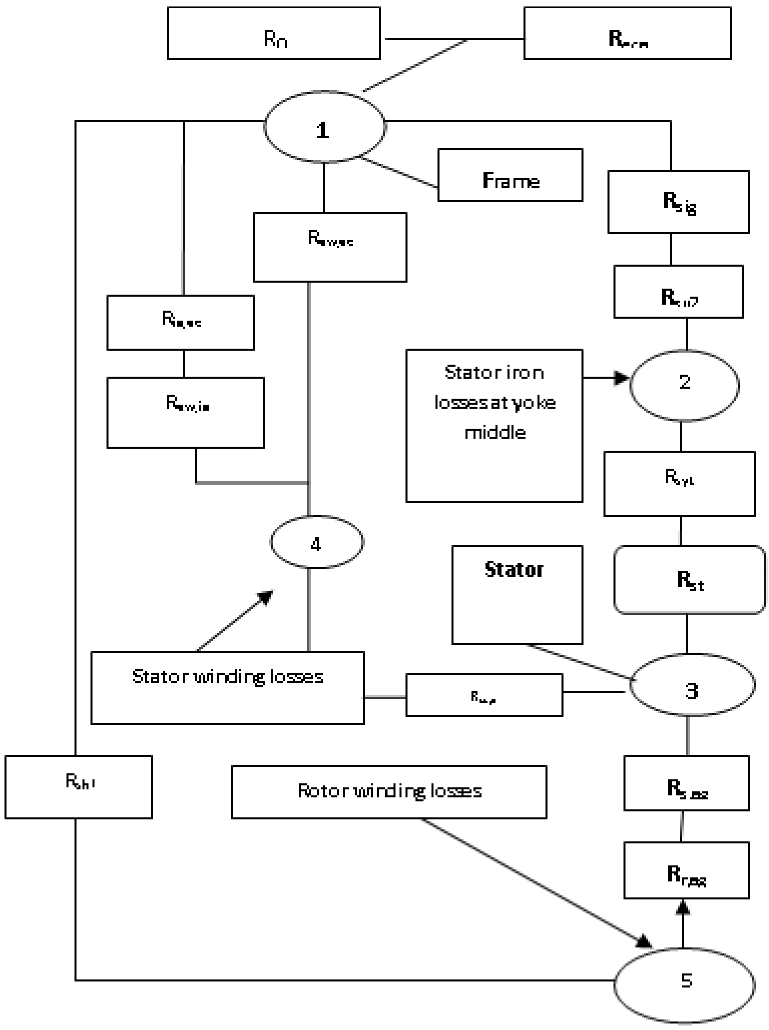


Figure 7: TNM of 5 Nodes

Table 8: Heat Distribution for the 5 Node TNM Model

NODE 1: Frame		**NODE 2 Stator**	
Node 4 to node 1	742.21	Node 2 to Node 4	-2.20
Node,3 to node 1	878.58	Node 2 to Node 3	-248.57
Node 5 to node 1	402.22	Node 5 to Node 2	250.78,,
Heat to ambient	-2023		
No heat generation at node 1		No heat generation at node 2	
NODE 3: Stator yoke middle		**NODE 4** Stator winding	
Node 1 to node 3	-878.6	Node 2 to node 4	2.20
Node 2 to node 3	248.57	Node 4 to node 1	- 742.20
Heat generation	630	Heat generation	740.00
NODE 5 Rotor winding			
Node 5 to node 1	-402.2	Heat generation	653
Node 5 to node 2	-250.78		

VII. PART F TNM OF ELEVEN NODES AND FIFTEEN THERMAL RESISTANCES [9]

This is an eleven node fifteen resistance model [9]. Axial variation of temperature is also considered. Only formation of governing equations and corresponding MATLAB program of this TNM is discussed in this report and application of this TNM has been done for the 7.5 KW motor.

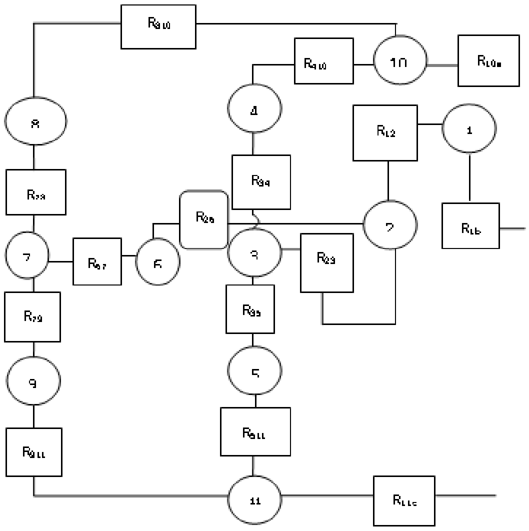


Figure 8: TNM of 11 Nodes

A. Governing Equations

$P_1 = \frac{1}{R_{12}}(\theta_2 - \theta_1) + \frac{1}{R_{1b}}(\theta_1 - \theta_b)$ $P_2 = \frac{1}{R_{12}}(\theta_2 - \theta_1) + \frac{1}{R_{23}}(\theta_2 - \theta_3) + \frac{1}{R_{26}}(\theta_2 - \theta_6)$

$P_3 = \frac{1}{R_{23}}(\theta_3 - \theta_2) + \frac{1}{R_{35}}(\theta_3 - \theta_5) + \frac{1}{R_{34}}(\theta_3 - \theta_4)$

$P_4 = \frac{1}{R_{34}}(\theta_4 - \theta_3) + \frac{1}{R_{410}}(\theta_4 - \theta_{10})$ $P_5 = \frac{1}{R_{511}}(\theta_5 - \theta_{11}) + \frac{1}{R_{35}}(\theta_5 - \theta_3)$

$P_6 = \frac{1}{R_{26}}(\theta_6 - \theta_2) + \frac{1}{R_{67}}(\theta_6 - \theta_7)$ $P_7 = \frac{1}{R_{79}}(\theta_7 - \theta_9) + \frac{1}{R_{78}}(\theta_7 - \theta_8) + \frac{1}{R_{67}}(\theta_7 - \theta_6)$

$P_8 = \frac{1}{R_{78}}(\theta_8 - \theta_7) + \frac{1}{R_{810}}(\theta_8 - \theta_{10})$ $P_9 = C_9 \frac{d\theta_9}{dt}, + \frac{1}{R_{911}}(\theta_9 - \theta_{11}) + \frac{1}{R_{79}}(\theta_9 - \theta_7)$

$P_{10} = \frac{1}{R_{410}}(\theta_{10} - \theta_4) + \frac{1}{R_{810}}(\theta_{10} - \theta_8) + \frac{1}{R_{10a}}(\theta_{10} - \theta_{ka})$

$P_{11} = \frac{1}{R_{511}}(\theta_{11} - \theta_5) + \frac{1}{R_{911}}(\theta_{11} - \theta_9) + \frac{1}{R_{11c}}(\theta_{11} - \theta_{kc})$

Table 9: Thermal Design of, 7.5 KW, 50HZ, 3-Ph Squirrel Cage Induction Motor

Resistance Values [9]							
r1b	r12	r23	r26	r11c	r35	r511	
0.041	0.015	0.035	0.14	0.015	0.18	1.89	
r67	r79	r91	r34	r410	r78	r810	r10a
0.004	0.11	0.93	0.175	1.89	0.10	0.93	0.02
Heat Flow Values Around The Nodes							

	Heat Flow Around Node 1 (Temp= 54.93)			
Q12	Q1b		P(1)	qsum1
1317.87	-1317.87		0.0	-0.000
Heat Flow Around Node 2 (Temp= 74.86)				
Q21	Q23	Q26	P(2)	Qsum2
-1317.87	841.27	137.59	339	-0.000
	Heat Flow Around Node 3(Temp=104.76)			
Q34	Q35	QSum3	P(3)	Q32
171.436	171.4362	0.0000	498.4	-841.27
Heat Flow Around Node 4(Temp=134.81)				

Q41	Q43	QSum4	P(4)	
	-171.4362	-70.3638	241.8	-0.0000
Heat Flow Around Node 5(Temp=134.81)				
Q511	Q53		P(5)	QSum5
-70.3638	-171.4362		241.8	0.0000
Heat Flow Around Node 6(Temp=93.76)				
Q62	Q67		P(6)	QSum6
-137.5953	58.5953		79	0.0000
	Heat Flow Around Node 7(Temp=94.01)			
Q62	Q67	QSum6	P(7)	
-58.5953	-66.7023	-66.702	192	-0.0000
Heat Flow Around Node 8(Temp=85.83)				
Q810	Q87	QSum8	P(8)	
-90.7023	66.7023		24	-0.0000
	Heat Flow Around Node 9(Temp=85.83)			
Q911	Q97	QSum9	P(9)	
-90.7023	66.7023		24	-0.0000
Heat Flow Around Node,10 (Temp=,2.40)				
Q108	Q104	Q10a	P(10)	Qsum10
90.7023	70.3638	-161.066	0.0	-0.0000
Heat Flow Around Node 11 (Temp= 2.40)				
Q119	Q115	Q11c	P(11)	Qsum11
90.7023	70.3638	-161.066	0.0	-0.0000

Conductivity values expressed as reciprocals of resistances

$G_{35}=1/R_{35}$; $G_{26}=1/R_{26}$; $G_{12}=1/R_{12}$; $G_{67}=/R_{67}$

$G_{410}=1/R_{410}$; $G_{511}=1/R_{511}$; $G_{23}=1/R_{23}$; $G_{78}=1/R_{78}$; $G_{79}=1/R_{79}$

$G_{810}=1/R_{810}$; $G_{911}=1/R_{911}$;

$G_{11} = G_{1a} + G_{12}$; $G_{22} = G_{12} + G_{26}$; $G_{33} = G_{35} + G_{34}$;

$G_{44} = G_{34} + G_{410}$; $G_{55} = G_{35} + G_{511}$; $G_{66} = G_{68} + G_{26}$;

$G_{77} = G_{79} + G_{78}$; $G_{88} = G_{810} + G_{87}$; $G_{99} = G_{79} + G_{911}$;

$G_{1010} = G_{810} + G_{10a}$; $G_{1111} = G_{911} + G_{11b}$;

R_{12} for instance, is the thermal resistance between the stator lamination and the stator winding. P_1 is the power loss in the frame while θ_1 is frame temperature rise respectively. By these definitions, the other variables could be established via the figure shown.

VIII PART G TNM OF TEN NODES AND THIRTY SEVEN THERMAL RESISTANCES

This is a model applied on a 30 KW motor geometry for which details are used to get temperature distribution. Evaluation of this ten node and thirty seven resistances is very detailed and evaluation of temperatures has been done by the same authors of this report [11] which also contains a MATLAB program for thermal distribution and the interested users may compare these results with 10 node TNM model. Method for determination of resistances also has been explained in the above report. Thus this model has not been explained separately and the reader is advised to go through the above said report for comparison with the above model.

CONCLUSIONS

- A genera MATLAB program has been deveoped in which soution of thermal distribution as per a particular TNM can be obtained by equating the value of variable TNM equa to no. of nodes of the TNM model.
- If the temperatures calculated at certain locations by a TNM of lesser number of nodes are critical or margnis of safety are quiet less it is advisable to use a TNM of slightly higher numbe of nodes before a recommendation for the change of design is recommended. In general, a higher TNM model makes fewer assumptions or simplifications and is closer to the actual engineering situations. The worth of a more accurate model, in terms of developmental difficulty encountered is generally the judgement of the user.

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APPENDICES

%Annexure

% MATLAB program - Temperature Estimation of Motors by % Different TNM Models

f2 = fopen('motor_gen_nodes.txt','w');

```
% Input TNM value corresponding to required TNM model

TNM=2;

if (TNM==5)|(TNM==2)

KW=30.0;kiron=39.0; ; visc_air=16.10*1.0e-6;

k_air=0.0304;visc_dyn_air=21.70e-06;Pr=0.708;

rho_air=1.029;cp_air=1.009*1.0e03;kcu=400.925;kal=237.0;

ang_vel=(2*pi*1500/60); fan_eff=0.5;

L=0.207;riy=.135;tec=riy*0.351;roy=riy*1.251;ris=riy*0.796; k_shaft=40;lag=0.80*1.0e-03;ror=ris-lag;slots=48;

rory=89*1.0e-03;riry=55*1.0e-03;Dout=roy*2;

loss_iron=630;loss_cu_stator=740;loss_cu_rotor=653;

Slot_area=230.84*1.0e-06; copper_area=190.64*1.0e-06;

shaf_exten=0.110;

lig=0.016 *1.0e-03; Lshf=0.750;kshaft=46;

fprintf(f2, 'Thermal Design of 30 KW,3-Phase SCIM \n');

slot_fill=0.5;L_end_wind = (0.12+1.15*ris/2)*1.5;

L_frame = (Lshf-shaf_exten);projection=L_end_wind;

Core_length=L;

area_end_cover=2*pi*(roy+tec)^2;

Tot_slot_area = Slot_area *slots;

tooth_area = (pi*(riy^2-ris^2) -Tot_slot_area) /slots;

pir = tooth_area/(Slot_area+tooth_area);

alpha=0.60 % Generally between 0.4 to 0.7

surf_area_a = 2*pi*roy*L_frame;

surf_area_b = area_end_cover;

tot_area = surf_area_a + surf_area_b;

fprintf(f2,'\n Length and rad slots core outer frame inner \n');

fprintf(f2,'\n - radius radius iron air shaft conductivities \n');

fprintf(f2,'%10.2f',L,ror,slots,riy,roy,kiron,k_air,kshaft);

fprintf(f2,'\n tooth outer rad rotor core rad frame thick \n');
```

```
fprintf(f2,'%9.3f',ris,rory,tec);

fprintf(f2,'\n tooth area tot_area slot area copper area \n');

fprintf(f2,'%11.2e',tooth_area,tot_area,Slot_area,copper_area);

% Forced Convection thermal resistance between external %case (Frame) and External air

% Resistance 1

R0 = 0.18/tot_area;

% Natural Convection thermal resistance between external %case (Frame) and External air

% Resistance 2

vel_air_1=ror*ang_vel*fan_eff;

vel_air_2=ror*ang_vel;

Re=vel_air_2*L_frame/visc_air;

Recr=100*(ris*lag)^0.5; % Critical reynold's number

Pr=cp_air*(visc_air*rho_air/k_air);

if (Re<1.0e04) Nu=0.66*Re^0.5*Pr^0.33

 else Nu =0.066*Re^0.75*Pr^0.33

end


hea=Nu*k_air/L_frame;

Ac=2*pi*roy*L_frame;

%Reca=1/(tot_area*hea);

Reca=1/(tot_area*hea);

% Resistance 3

% Convection thermal resistance between inner air and the %External frame

hec=15.5*(1+0.29*vel_air_1);Riaec = 1.0/(area_end_cover*hec);

fprintf(f2,'\n velocity Re Pr Nu hea Reca hec \n');

fprintf(f2,'%10.2f',vel_air_2, Re, Pr, Nu, hea, Reca,hec);

% Resistance 4 (One half of the Radial conduction thermal %resistances of the Stator Yoke (Inner Part)

rm=(riy+roy)/2.0;

R_sy1=(1/(2*pi*kiron*Core_length))*log(rm/riy);
```

% Resistance 5 (One half of the Radial conduction thermal %resistances of the Stator Yoke (Outer Part)

R_sy2=(1/(2*pi*kiron*Core_length))*log(roy/rm);

% kair=0.0000795*Tmean+0.00246;

Resistance 6

% Radial Conduction Thermal resistance of the Stator teeth

Rst=(1/(2*pi*kiron*Core_length*pir))*log(riy/ris);

%Resistance 7

lsb=2*pi*(riy +ris)/2.0*(1-pir)/slots;

% Conduction Thermal resistance Between Stator CU & Fe

keqcu=0.2749*((1-slot_fill)*Slot_area*Core_length)^-0.4471;

teq= Slot_area*(1-slot_fill) /lsb;

Rcuir=teq/(keqcu*Slot_area);

hsig=lig/k_air;

fprintf(f2,'\n lig tec teq lsb slot fill length of length of keq of h equi of \n');

fprintf(f2,'\n factor shaft frame copper air gap \n');

fprintf(f2,'%10.2e',lig,tec,teq,lsb,slot_fill,Lshf)

fprintf(L_frame,keqcu,hsig);

% Resistance 8

% Conduction thermal resistance between stator winding %external connection and external case(frame)

yoke_height = (roy-riy); tsy = yoke_height;

Rewec_a=2*pi*kiron*projection;

roy_b=(roy-alpha*tsy);

Rewec_b= log(roy/roy_b);

Rewec= Rewec_b/Rewec_a;

% Resistance 9 Convection Thermal Resistance between %Stator (end winding) and Inner Air

Aew=2*pi*ris*projection;

vel_air_1=ror*ang_vel*fan_eff;

hew=15.5*(1+ 0.29*vel_air_1);

```
Rewia=1/(Aew*hew) ;

% Resistance 10

% Convection Thermal Resistance between Stator and air gap

Nu=2;

hag=Nu*k_air/(2*lag);

Aist=2*pi*ris*Core_length;

R_sag=1/(Aist*hag);

% Resistance 11

% Convection Thermal Resistance between Rotor and airgap

Aort=2*pi*ror*Core_length;

R_rag=1/(Aort*hag);

Rairgap=(1/(2*pi*k_air*Core_length))*log(ris/ror);

% Resistance 12

% Interface Gap Conduction Resistance (Thermal contact %resistance) Between Stator core and frame (external case)

hsig=lig/k_air;

Rsig=lig/(2*k_air*pi*roy*Core_length);


% Resistance 13

% Resistance is in three parts ( %Part 1 due to the rotor yoke,


Rshf1= 1/(2*pi*kshaft*Core_length)*log(rory/riry)

Rshf2= 0.25*0.5*Core_length/(kshaft*pi*riry^2)

% second one takes into account the shaft part

% below the rotor core

Rshf3= 0.5*0.5*shaf_exten/(kshaft*pi*riry^2) ;


%and the last one is the equivalent axial thermal

% resistance due to the shaft part external

% to the rotor core length
```

```
Rshf= Rshf1 +Rshf2 +Rshf3;


R1=Reca; R2=R0; R3= Riaec; R4= R_sy1; R5= R_sy2; R6= Rst; R7 =Rcuir;
R8= Rewec; R9 =Rewia; R10=R_sag; R11=R_rag; R12=Rsig;R13=Rshf;
end;
if TNM==5
g15= (1/Rshf)+ (1/Reca);
r14_a= Riaec + Rewia;
r14_b= Rewec ;
g14 = r14_a * r14_b/(r14_a + r14_b) ;
% g14 = (r14_a + r14_b)/(r14_a * r14_b) + (1/Reca);
g12 = 1/(Rsig+R_sy2);g21=g12;
g13=0.0;
g11= (g12+g14+g15);
g31=0.0;
g23= 1/(R_sy1 + Rst);
g34= 1/Rcuir;
g35= 1/(R_sag +R_rag);
% g35= 1/Rairgap;
g22 = (g21+g23);g32=g23;g33= g32+g34+g35;
g41=g14;g43=g34;g44=g41+g43;
g51=g15;g53=g35;g55=g51+g53;


%% Matrix %%
condu = [ g11 -g12 0.0 -g14 -g15;
 0.0 g22 -g23 0.0 0.0;
 0.0 -g23 g33 -g34 0.0;
 -g41 0.0 -g43 g44 0.0;
 -g51 0.0 -g53 0.0 g55];
```

```
p = [0;    loss_iron; 0; loss_cu_stator; loss_cu_rotor ];


p1=p;
temp=condu\p1;
f_Row= [g11 -g12 0.0 -g14 -g15 ];
s_Row= [ 0.0 g22 -g23 0.0 0.0] ;
t_Row= [ 0.0 -g23 g33 -g34 0.0 ];
fo_Row=[-g41 0.0 -g43 g44 0.0 ];
fi_Row=[ -g51 0.0 -g53 0.0 g55 ];


%Heat flow around node 1
q15= (temp(1)-temp(5))/Rshf;
r14_a= Riaec + Rewia;
r14_b= Rewec ;
q14 = (temp(1)-temp(4))*(r14_a + r14_b)/(r14_a * r14_b);
q12 = (temp(1)-temp(2))/(Rsig+R_sy2);
q1a= temp(1)/Reca;
qsum1=q14+q12+q1a+q15-p1(1);
fprintf(f2,'\nHeat flow around node 1 \n');
fprintf(f2,' q15 q14 q12 heat dissipated to ambient heat generated and total loss ');
fprintf(f2,'\n');
fprintf(f2,'%10.2f',q15,q14,q12,q1a,-p1(1),qsum1);fprintf(f2,'\n');
q32= (temp(3)-temp(2))/(R_sy1 + Rst);
q34= (temp(3 )-temp(4))/Rcuir;
q35= (temp(3)-temp(5))/(R_sag+R_rag);
%Heat flow around node 2
q21 =-q12;
q23= -q32;
qsum2=q21+q23-p1(2);
```

```
fprintf(f2,'Heat flow around node 3 \n');

fprintf(f2,' q31 q32 heat generated at third node and sum of losses ');fprintf(f2,'\n');

fprintf(f2,'%10.4f',q21,q23,-p1(2),qsum2);fprintf(f2,'\n');


%Heat flow around node 3


qsum3=q32+q34+q35-p1(3);

fprintf(f2,'Heat flow around node 2 \n');

fprintf(f2,' q23 q24 q25 heat generated at second node and total loss ');fprintf(f2,'\n');

fprintf(f2,'%10.4f',q32,q34,q35,-p1(3),qsum3);fprintf(f2,'\n');


%Heat flow around node 4

q41=-q14;q43=-q34;qsum4=q41+q43 -p1(4);

fprintf(f2,'Heat flow around node 4 \n');

fprintf(f2,' q41 q43 loss at IV node & qsum 4 ');

fprintf(f2,'\n');

fprintf(f2,'%10.4f',q41,q43,-p1(4),qsum4);fprintf(f2,'\n');


%Heat flow around node 5

q51=-q15;

q53=-q35;

qsum5=q51+q53 -p1(5);

fprintf(f2,'Heat flow around node 5 \n');

fprintf(f2,' q51 q53 loss at V node and qsum5 ');

fprintf(f2,'\n');fprintf(f2,'%10.4f',q51,q53,-p1(5),qsum5);


fprintf(f2, '\n--------------conductivity matrix ');fprintf(f2,'\n');

fprintf(f2,'%8.2f',f_Row);fprintf(f2,'\n');

fprintf(f2,'%8.2f',s_Row);fprintf(f2,'\n');
```

```
fprintf(f2, '%8.2f',t_Row);fprintf(f2,'\n');

fprintf(f2, '%8.2f',fo_Row);fprintf(f2,'\n');

fprintf(f2, '%8.2f',fi_Row);fprintf(f2,'\n');

fprintf(f2, '\nTemperature rise in the nodes');

fprintf(f2,'%9.2f',temp);

fprintf(f2, '\nHeat in puts in the nodes');

fprintf(f2,'%9.2f',p1);


end;


if TNM==2

Rsp1=Riaec + Rewia;

Rsp2=Rewec ;

Rs1= (Rsp1 * Rsp2 /(Rsp1 + Rsp2))+Rcuir;

Rs2= Rsig + R_sy1 +R_sy2 + Rst

Rsoverall= Rs1 * Rs2 /( Rs1 + Rs2);

Rs = Rsoverall +(1/Reca);

Rr = Rshf;

% Rsr= R_rag;

Rsr= R_sag;

% Rsr= Rairgap;

q11 = 1/Rs+ 1/Reca;q12 = 1/Rsr;

q22 = 1/Rr ;

%R_sag - Static conditions of air gap heat transfer

%R_rag - Rotary conditions of air gap heat transfer


%% Matrix %%

condu = [ q11 -q12; -q12 q22 ] ;
```

```
loss_stator=loss_iron+loss_cu_stator;
loss_rotor=loss_cu_rotor;
p = [loss_stator;
 loss_rotor];
%temp= [110; 200];
%p=condu*temp ;
temp=condu\p;

fprintf(f2,'\n Rs r12 Rr\n');
fprintf(f2,'%10.4f',Rs,Rsr,Rr);

fprintf(f2, '\n--------------conductivity matrix ');fprintf(f2,'\n');
fprintf(f2,'%8.2f',q11,-q12);fprintf(f2,'\n');
fprintf(f2,'%8.2f',-q12,q22);fprintf(f2,'\n');
fprintf(f2, '\n--------------temperature matrix ');fprintf(f2,'\n');
fprintf(f2,'%8.2f',temp);fprintf(f2,'\n');

fprintf(f2, '\nTemperature rise in the nodes');
fprintf(f2,'%9.2f',temp);

fprintf(f2, '\nHeat in puts in the nodes');
fprintf(f2,'%9.2f',p);
end;
if (TNM==5)|(TNM==2)
fprintf(f2,'\n R1 R2 R3 R4 R5 R6 \n');
fprintf(f2,'%10.3f',R1,R2,R3,R4,R5,R6);
fprintf(f2,'\n R7 R8 R9 R10 R11 R12 R13\n');
fprintf(f2,'%10.3f',R7,R8,R9,R10,R11,R12,R13);
end;
```

```
if TNM==4

% TNM of four nodes and six thermal resistances

r1a= 0.0416; r12 = 10.75e-03;r13= 0.135; r24=0.160; r34=0.0948;r4b=0.015;

g1a=1/r1a; g12=1/r12;g13=1/r13;g14=0.0;

g24=1/r24;g34=1/r34;g4b=1/r4b;g23=0.0;

g11 = g13 + g12+1/r1a;

g22 = g12 +g24;

g33 = g13 + g34 ;

g44 = g24 + g34 +1/r4b;


%% Matrix %%

% pad=68.0;pf=22;ps=485;pr=125;ph=160;

pad=68.0;pf=22;ps=374;pr=118.5;ph=123.80;


p1=ph+0.3 *pad; p2=ps+0.4*pad;

p3=pr+pf +0.3*pad; p4=0.0;


g = [g11 -g12 -g13 -g14 ;   -g12 g22 -g23 -g24 ;

 -g13 -g23 g33 -g34 ;          -g14 -g24 -g34 g44 ];

p = [p1; p2; p3; p4;];

t=g\p;


q1a=t(1)/r1a;

q4b=t(4)/r4b;

q24=abs(t(2)-t(4))/r24; q34=abs(t(3)-t(4))/r34

q13=abs(t(3)-t(1))/r13; q12=abs(t(2)-t(1))/r12

pin1=pad+pf+ps+pr+ph

pin2=p1+p2+p3+p4

p1sum=p1-q1a+q12-q13; p2sum=p2-q12-q24
```

```
p3sum=p3+q13-q34; p4sum=p4+q34+q24-q4b
qsum=p1sum+p2sum+p3sum+p4sum
fprintf(f2, '\n--------------conductivity matrix ');fprintf(f2,'\n');
fprintf(f2,'%8.2f',g11,-g12, -g13, -g14,1/r1a);fprintf(f2,'\n');
fprintf(f2,'%8.2f',-g12,g22,-g23,-g24);fprintf(f2,'\n');
fprintf(f2,'%8.2f',-g13,-g23,g33,-g34);fprintf(f2,'\n');
fprintf(f2,'%8.2f',-g14,-g24,-g34,g44,1/r4b);fprintf(f2,'\n');
fprintf(f2, '\n-Thermal resistances along ix various paths ');
fprintf(f2,'\n');
fprintf(f2,'%8.2f',r1a,r4b,r24,r34,r13,r12);fprintf(f2,'\n');
fprintf(f2, '\n-----------Heat flows along the six various paths ');
fprintf(f2,'\n');
fprintf(f2,'%8.2f',q1a,q4b,q24,q34,q13,g12);fprintf(f2,'\n');

fprintf(f2, '\n--------------temperature matrix ');fprintf(f2,'\n');
fprintf(f2,'%8.2f',t);fprintf(f2,'\n');
fprintf(f2, '\n--------------heat input matrix ');fprintf(f2,'\n');
fprintf(f2,'%8.2f',p);fprintf(f2,'\n');
end;
if(TNM==6)
r14=1.0;r12=1.0;r45=1.0; r34=1.0;r26=1.0;
r56= 1.0;r36 = 1.0;r50=1.0;
g14=1/r14; g12=1/r12; g26=1/r26; g45= 1/r45;
g34 = 1/r34; g36 = 1/r36; g56=1/r56; g50=1/r50;
g11 = g12 +g14; g22 = g12+g26; g33 = g34 + g36 ;
g44 = g14 + g45; g55 = g45 +g56 ;g66 = g36 + g26+ g56;
%% Matrix %%
pad=130;% %stray losses or additional losses =130
pf=40;ps=930;pr=240;ph=300;
```

```
p5=0;p6=0.0;p7=0.0;p8=0.0;
p1=ps*0.52;p2=ps *.48 + 0.4*pad;
p3=ph;p4=ph;p5=pr;p6=0.6*pad+pf;
g = [g11 -g12 0 -g14 0 0 ;
 -g12 g22 0 0 0 -g26 ;
0 0 g33 -g34 0 -g36 ;
 -g14 0 -g34 g44 -g45 0 ;
 0 0 0 -g45 g55 -g56 ;
 0 -g26 -g36 0 -g56 g66 ];
p = [p1; p2; p3; p4; p5; p6];
t=g\p
end;
if TNM==8
r14=1.0;r12=1.0;
r45=1.0; r13=1.0;r26=1.0;
r58= 1.0;r37 = 1.0;r36 = 1.0;r68= 1.0;r50=1.0;r70=1.0; r80=1.0;
g14=1/r14; g12=1/r12; g45=1/r45; g13=1/r13; g26=1/r26;
g58= 1/r58; g37 = 1/r37; g36 = 1/r36; g68= 1/r68; g50=1/r50; g70=1/r70; g80=1/r80;
g11 = g13 + g12+g14; g22 = g12 +g26;
g33 = g37 + g36 + g13;
g44 = g14 + g45;            g55 = g45 +g50 +g58; g66 = g26 + g68+ g36; g77 = g37 + g70+g13; g88 = g68+g80;
%% Matrix %%
pad=130;% %stray losses or additional losses =130
pf=40;ps=930;pr=240;ph=300;
p5=0;p6=0.0;p7=0.0;p8=0.0;
p1=ps*0.52; p2=ps *.48 + 0.4*pad; p3=pr; p4=ph; p6=0.3*pad+pf;
g = [g11 -g12 -g13 0 0 0 0 0 ;
 -g12 g22 0 0 0 -g26 0 0 ;
          -g13 0 g33 0 0 -g36 -g37 0 ;
```

```
 -g14 0 0 g44 -g45 0 0 0 ;
 0 0 0 -g45 g55 0 0 -g58 ;
 0 -g26 -g36 0 0 g66 -g58 -g68 ;
 0 0 -g37 0 0 0 g77 0 ;
 0 0 0 0 -g58 -g68 0 g88 ];
p = [p1; p2; p3; p4; p5; p6; p7; p8];
t=g\p
end;
if TNM==11
r1b= 0.0416; r12 = 15.44e-03;r23= 35.58e-03; r26=0.135; r11c=0.015;r35=0.1751; r511=1.886; r67=4.115e-03;
r79=0.1055;r911=0.932;
r34=r35;r410=r511;r78=r79; r810=r911;r10a=r11c;
g34=1/r34; g410=1/r410;g78=1/r78;g810=1/r810;
g1b= 1/r1b;g12 = 1/r12;g23= 1/r23; g26=1/r26; g11c=1/r11c;g10a=1/r10a;
g35=1/r35; g511=1/r511; g67=1/r67; g79=1/r79; g911=1/r911;
g11 = g1b + g12;
g22 = g12 +g23+g26;
g33 = g23 + g34 + g35;
g44 = g410 + g34;
g55 = g35 +g511 ;
g66 = g26 + g67;
g77 = g78 + g79+g67;
g88 = g78+g810;
g99 = g79 + g911;
g1010= g410+g10a +g810;
g1111= g511 + g11c+g911;
%% Matrix %%
pad=130;% %stray losses or additional losses =130
pf=40;ps=930;pr=240;ph=300;
```

```
p1=0;p2=ph + 0.3*pad;
p3=ps *.48 + 0.4*pad; %Stator winding
p4=ps*0.52/2;%Stator end winding
p5=ps*0.52/2;%Stator end winding
p6=0.3*pad+pf;
p7=pr*0.8; %Rotor copper losses
p8=0.1*pr;%End ring
p9=0.1*pr; %End ring
p10=0.0;p11=0.0;
g = [g11 -g12 0 0 0 0 0 0 0 0 0 ;
 -g12 g22 -g23 0 0 -g26 0 0 0 0 0 ;
        0 -g23 g33 -g34 -g35 0 0 0 0 0 0 ;
 0 0 -g34 g44 0 0 0 0 0 -g410 0 ;
 0 0 -g35 0 g55 0 0 0 0 0 -g511;
 0 -g26 0 0 0 g66 -g67 0 0 0 0;
 0 0 0 0 0 -g67 g77 -g78 -g79 0 0;
 0 0 0 0 0 0 -g78 g88 0 -g810 0;
 0 0 0 0 0 0 -g79 0 g99 0 -g911 ;
 0 0 0 -g410 0 0 0 -g810 0 g1010 0;
 0 0 0 0 -g511 0 0 0 -g911 0 g1111];
p = [0.0; p2; p3; p4; p5; p6; p7; p8; p9; 0; 0];
t = [ 34.71; 47.60; 62.96; 71.26; 71.26;63.670; 64.120; 68.30;68.30; 6.2;6.2];
t=g\p
f_Row= [g11 -g12 0 0 0 0 0 0 0 0 0 ];
s_Row= [-g12 g22 -g23 0 0 -g26 0 0 0 0 0] ;
t_Row= [ 0 -g23 g33 -g34 -g35 0 0 0 0 0 0 ];
fo_Row=[ 0 0 -g34 g44 0 0 0 0 0 -g410 0];
fi_Row=[ 0 0 -g35 0 g55 0 0 0 0 0 -g511 ];
si_Row=[ 0 -g26 0 0 0 g66 -g67 0 0 0 0];
se_Row=[ 0 0 0 0 0 -g67 g77 -g78 -g79 0 0];
ei_Row=[ 0 0 0 0 0 0 -g78 g88 0 -g810 0];
ni_Row=[ 0 0 0 0 0 0 -g79 0 g99 0 -g911] ;
te_Row=[ 0 0 0 -g410 0 0 0 -g810 0 g1010 0];
le_Row=[ 0 0 0 0 -g511 0 0 0 -g911 0 g1111];
```

```
fprintf(f2, 'Thermal Design of 7.5 KW,SCIM Motor\n');
fprintf(f2, ***************************************');
fprintf(f2,'\n r1b r12 r23 r26 r11c r35 \n');
fprintf(f2,'%10.4f',r1b,r12,r23,r26,r11c,r35);
fprintf(f2,'\n r511 r67 r79 r911 r34 r410 \n');
fprintf(f2,'%10.4f',r511,r67,r79,r911,r34,r410);
fprintf(f2,'\n r78 r810 r10a \n');
fprintf(f2,'%10.4f',r78,r810,r10a);
fprintf(f2, '\n heat input values:');
fprintf(f2,'\n');
pad=130;% %stray losses or additional losses =130
pf=40;ps=930;pr=240;ph=300;
fprintf(f2,' iron loss=%5.1f,additional loss=%5.1f,frictional loss=%5.1f',ph,pad,pf);
fprintf(f2,'\nstator copper loss=%5.1f, rotor copper loss=%5.1f',ps,pr);
fprintf(f2, '\n--------------conductivity matrix ');fprintf(f2,'\n');
fprintf(f2,'%7.2f',f_Row);fprintf(f2,'\n');
fprintf(f2,'%7.2f',s_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',t_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',fo_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',fi_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',si_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',se_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',ei_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',ni_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',te_Row);fprintf(f2,'\n');
fprintf(f2, '%7.2f',le_Row);fprintf(f2,'\n');
q12= (t(1)-t(2))/r12;q23= (t(2)-t(3))/r23;
q10a= t(10)/r10a;
q1=t(1)/r1b;q11c= t(11)/r11c;
q511= (t(5)-t(11))/r511;
q67= (t(6)-t(7))/r67;q78= (t(8)-t(7))/r78;
q108= (t(8)-t(10))/r810;
q79= (t(9)-t(7))/r79;q911= (t(9)-t(11))/r911;
q26= (t(2)-t(6))/r26;
%Heat flow around node 1
q12= (t(2)-t(1))/r12;q1b= -(t(1))/r1b;
qsum1=q12+q1b+p(1);
%Heat flow around node 2
q21= -q12;q23= (t(3)-t(2))/r23;q26= (t(6)-t(2))/r26;
```

```
qsum2=q21+q23+q26+p(2);
%Heat flow around node 3
q34= (t(4)-t(3))/r34;q32= -q23;
qsum3=q34+q35+q32+p(3);
fprintf(f2,'\n heat flow around node 1 q12 q1b qsum1 \n');
fprintf(f2,'%10.4f',q12,q1b,qsum1);
fprintf(f2,'\n flow -node 2 q21 q23 q26 p(2) qsum2 \n');
fprintf(f2,'%10.4f',q21,q23,q26,p(2),qsum2);
fprintf(f2,'\n Flow node 3 q34 q35 q32 p(3) qsum3 \n');
fprintf(f2,'%10.4f',q34,q35,q32,p(3),qsum3);
%Heat flow around node 4
q410= (t(10)-t(4))/r410;q43= -q34;
qsum4=q43+q410+p(4);
fprintf(f2,'\n Around node 4 q410 q43 p(4) qsum4 \n');
fprintf(f2,'%10.4f',q410,q43,p(4),qsum4);
%Heat flow around node 5
q511= (t(11)-t(5))/r511;q53= -q35;
qsum5=q53+q511+p(5);
fprintf(f2,'\n Around node 5 q511 q53 p(5) qsum5 \n');
fprintf(f2,'%10.4f',q511,q53,p(5),qsum5);
%Heat flow around node 6
q62= -q26; q67= (t(7)-t(6))/r67;qsum6=q62+q67+p(6);
fprintf(f2,'\n flow around node 6 q62 q67 p(6) qsum6 n');
fprintf(f2,'%10.4f',q62,q67,p(6),qsum6);
%Heat flow around node 7
q76= -q67;q79= (t(9)-t(7))/r79;q78= (t(8)-t(7))/r78;
qsum7=q76+q79+q78+p(7);
fprintf(f2,'\n heat flow around node 7 q76 q79 q78 qsum7 \n');
fprintf(f2,'%10.4f',q76,q79,q78,p(7),qsum7);
%Heat flow around node 8
q810= (t(10)-t(8))/r810; q87= -q78;
qsum8=q87+q810+p(8);
fprintf(f2,'\n heat flow around node 8 q810 q87 qsum8 \n');
fprintf(f2,'%10.4f',q810,q87,p(8),qsum8);
%Heat flow around node 9
q911= (t(11)-t(9))/r911;q97= -q79;
qsum9=q97+q911+p(9);
fprintf(f2,'\n heat flow around node 9 q911 q97 qsum9 \n');
fprintf(f2,'%10.4f',q911,q97,p(9),qsum9);
%Heat flow around node 10
```

```
q108= -q810;q104=-q410;q10a= -t(10)/r10a;
qsum10=q104+q108+q10a+p(10);
fprintf(f2,'\n Flow around 10 q108 q104 q10a qsum10 \n');
fprintf(f2,'%10.4f',q108,q104,q10a,p(10),qsum10);
%Heat flow around node 11
q119= -q911;q115=-q511;q11c= -t(11)/r11c;
qsum11=q119+q11c+q115+p(11);
fprintf(f2,'\n flow around 11- q119 q115 q11c qsum11 \n');
fprintf(f2,'%10.4f',q119,q115,q11c,p(11),qsum11);
fprintf(f2, '\nTemperature rise in the nodes');
fprintf(f2,'%7.2f',t);fprintf(f2, '\nHeat in puts in the nodes');
fprintf(f2,'%7.2f',p);
end;
fclose(f2);
```